Shoaling Wave Energy Dissipation in Turbulent Bottom Boundary Layers

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LONG-TERM GOAL

The long term goal is to increase the understanding and predictive capability for effects of turbulent bottom boundary layers on shoaling wave fields.

OBJECTIVES

The present objectives are to make direct estimates of shoaling surface wave energy dissipation rates that occur in the bottom boundary layer for different wave field and mean current conditions for different bottom topographies including realistic sand ripples. The three-dimensional direct numerical simulations are being used to evaluate one-dimensional eddy viscosity models such as proposed by Trowbridge and Madsen (1984). We are also examining the dependence of the boundary layer thickness and the vertical transport of mass and momentum within the boundary layer as a function of the surface wave field and bottom topography.

APPROACH

The work involves theoretical analysis, numerical computations, and comparison with field and laboratory results. The primary experimental tools are three-dimensional direct numerical simulations (DNS) (Slinn and Riley, 1998) and large eddy simulations (LES) of turbulent flows occurring in the wave bottom boundary layer. Our models resolve the relevant scales of motion in the strong shear layer at the sea floor.

WORK COMPLETED

There are presently two graduate students doing M.S. theses on this project. (1) Stephanie Moneris is focusing on oscillatory flow over a smooth bottom surface including mean currents of varying strength normal to the direction of the wave oscillation. This situation is analogous to shoaling waves in an environment with an alongshore current. (2) Thomas Pierro is using a new bottom boundary layer model, developed in collaboration with Kraig Winters (University of Washington), for LES and DNS simulations of flow over small scale topographic variability (e.g., sand ripples). This model establishes a significant new capability for our work, in which the Navier-Stokes equations are solved in a curvilinear terrain conforming coordinate system (sigma coordinates) for arbitrarily complex bottom topographies. In these experiments the boundary layer for simple oscillatory wave driven flows are compared to uni-directional flows over sand ripples of different wavelength, amplitude, and shape.

RESULTS

Including a mean current to the wave bottom boundary layer, normal to the direction of wave oscillation, changes the flow behavior significantly. The ratio of the strength of the mean current to the magnitude of the oscillatory current, V_∞ / U_∞, is a key parameter. Turbulent kinetic energy (TKE) as a function of time and distance from the bottom boundary for different ratios of V_∞ / U_∞ is shown for four experiments in Figure 1 with wave period, $2\pi / \omega = 5$ s. With no mean flow, $V_\infty = 0$, the

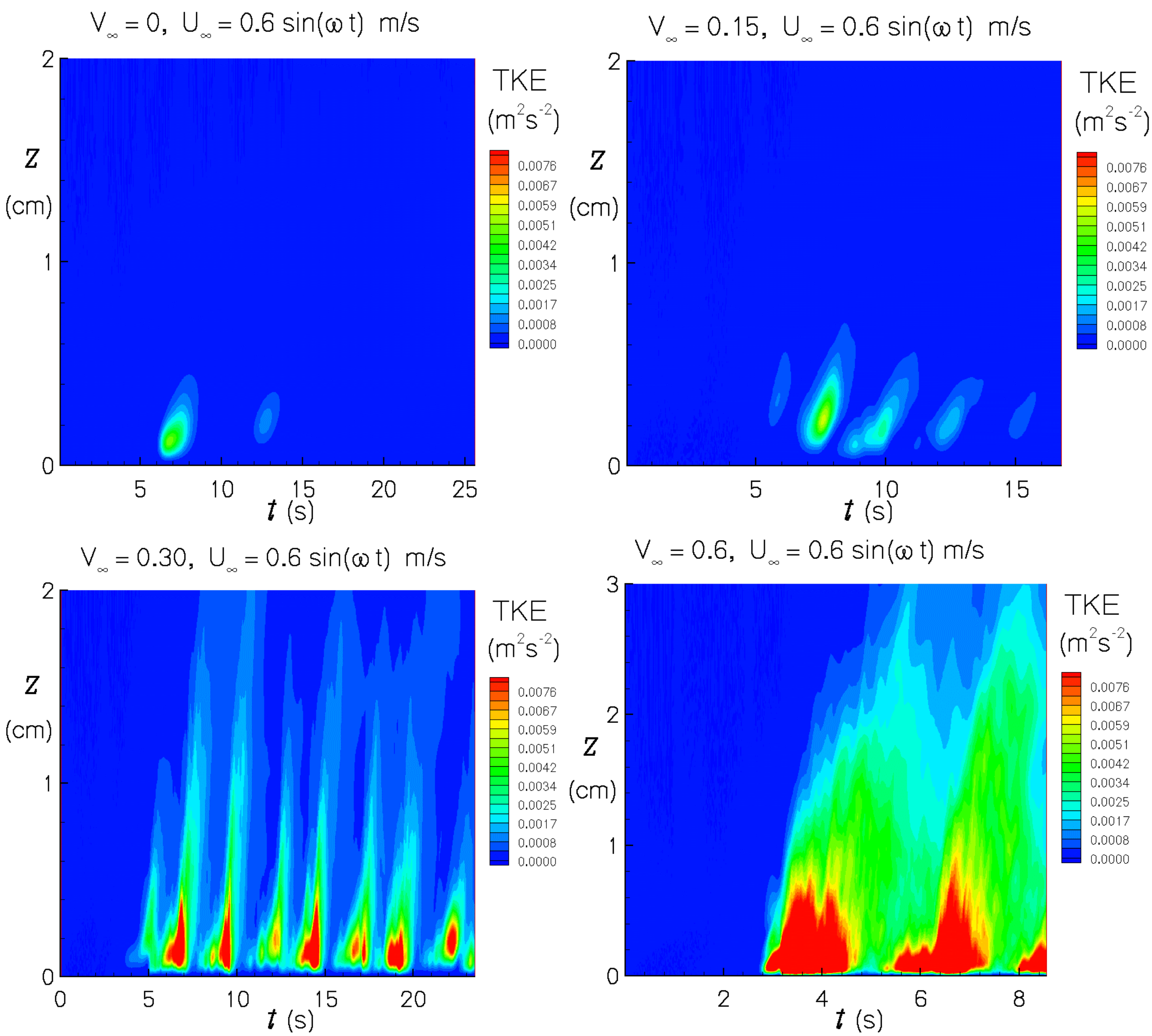

Figure 1: Average turbulent kinetic energy as a function of time and distance from the bottom boundary for combined wave and oscillatory flow over a smooth bottom boundary. Here the wave period is 5 seconds, the mean flow velocity above the boundary layer is varied between zero and 0.6 m/s and the peak wave induced near bed velocity is 0.6 m/s.

boundary layer is margninally stable, and after two weakly turbulent events associated with startup transients the flow in the boundary layer remains laminar. When a weak mean current is added, panel 2, upper right, the flow is slightly more turbulent and turbulent events persist through more flow reversal events. In the third experiment, with $V_\infty = 0.30$ m/s, the turbulence is stronger, episodic, and continually repeats during each phase of flow deceleration and reversal. In the final case shown, $V_\infty = U_\infty$, the turbulence is much stronger and persists from one event to the next.

Flow over variable topography is illustrated in Figures 2 – 4. Figure 2 depicts velocity vectors during a phase of flow over a sinusoidal sand ripple with amplitude of 1 cm and wavelength of 10 cm (aspect ratios are not to scale). These flows have been found to be much more turbulent than flows over smooth flat bottoms. The boundary layer thickness increases and the duration of turbulent bursts is much longer. Flow separation occurs in the lee of the ripple crests during phases of strong onshore or offshore flow. The flows are highly time dependent. Figure 3 shows a close up of velocity profiles on the downslope behind the sand ripple crest. Figure 4 illustrates the more general capabilities of the curvilinear coordinate system model. Here the bottom topography is the sum of 3 different frequencies of sine waves. The model is capable of any periodic bottom topography that can be represented as Fourier series components, which in general can match nearly any desired shape. In the geometry depicted in Figure 4 we use 512 x 33 x 65 grid points in the *x, y*, and *z* directions respectively, and could therefore have used up to 512 Fourie components to represent a complex skewed sand ripple similar to those observed in nature. The domain modeled is 50 cm x 5 cm x 5 cm. We are just beginning to explore the flow behavior for different wave field conditions, primarily varying the wave frequency and amplitude, and for different sand ripple topographic features.

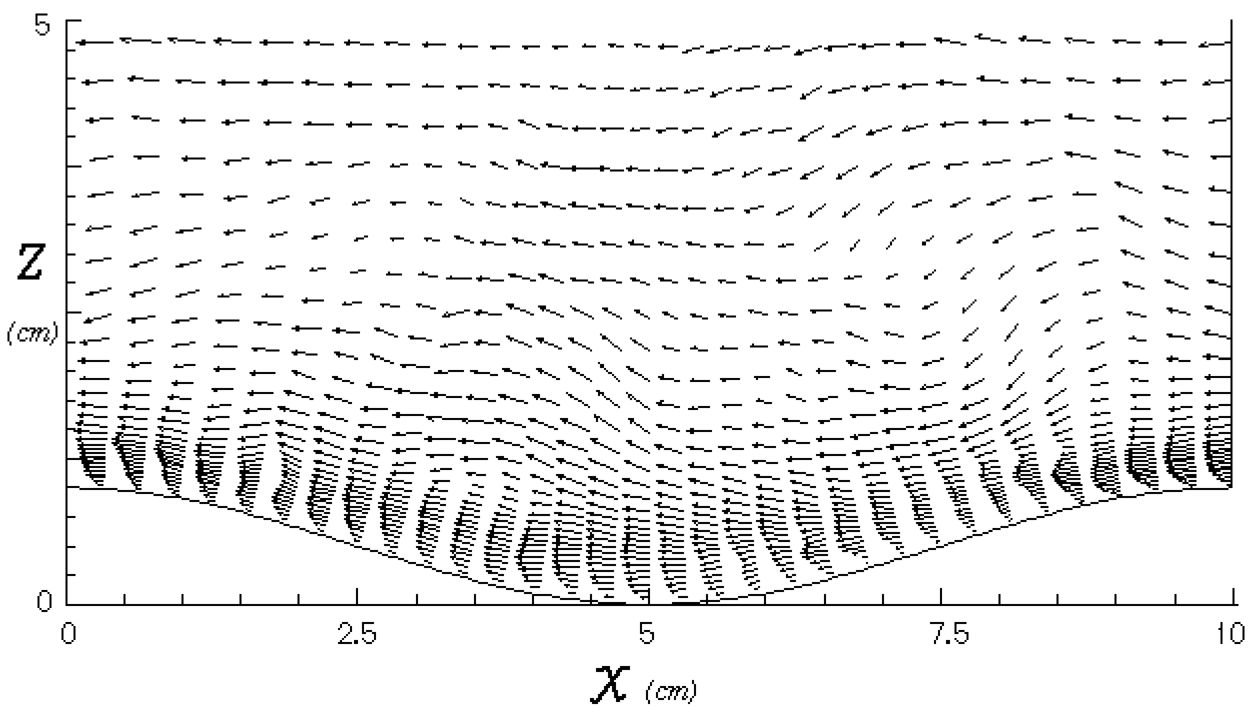

Figure 2: Velocity vectors in a 2-D plane (from a 3-D simulation) of oscillatory flow over a sand ripple.

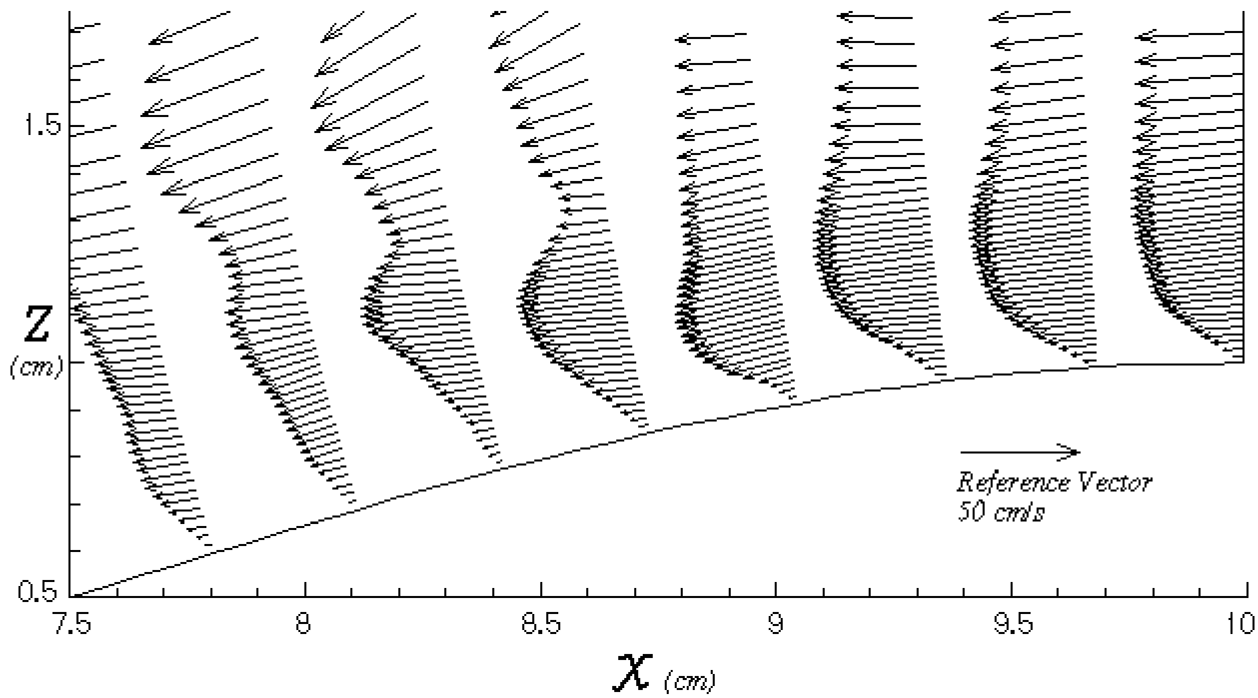

Figure 3: Close up of velocity vectors near the bottom boundary show a region where the boundary layer separates from the wall behind the crest of the sand ripple. Velocity profiles are shown at every 4th along stream grid location to emphasize profile changes.

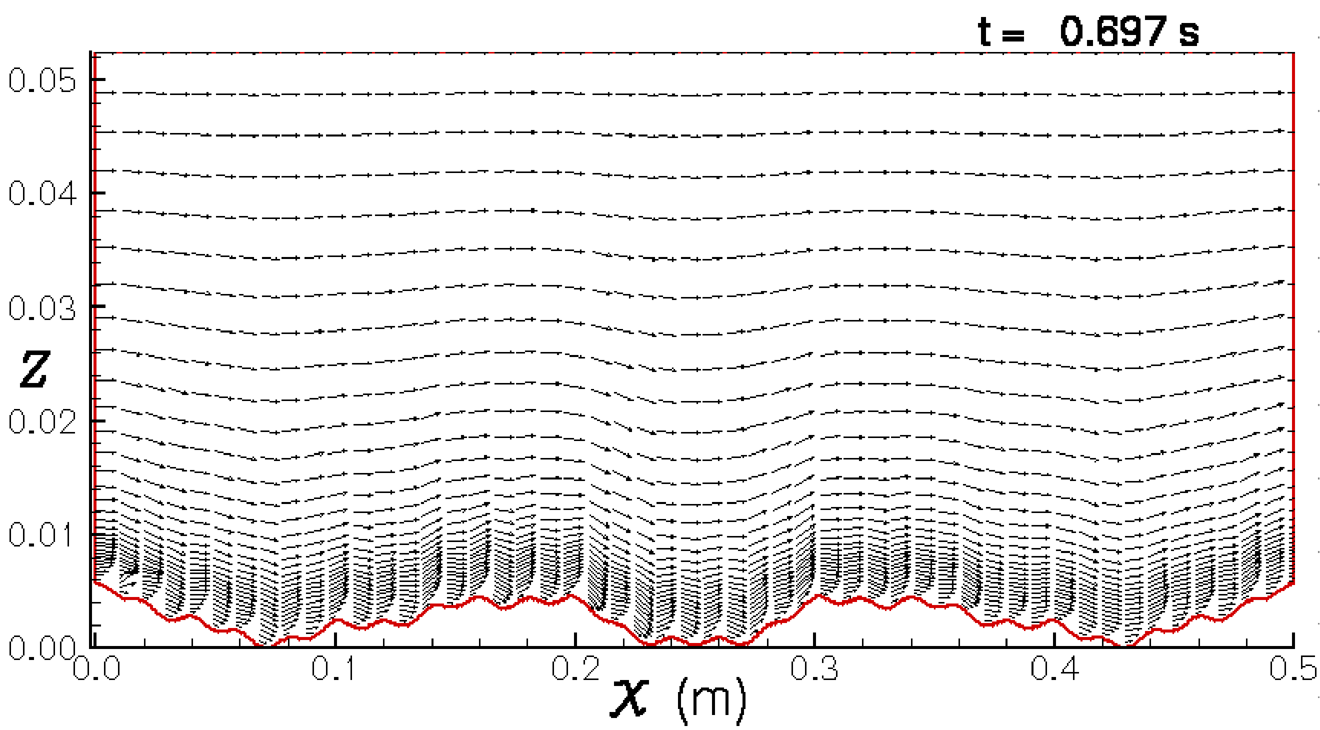

Figure 4: Velocity vectors in a 2-D plane (from a 3-D simulation) of oscillatory flow over a bumpy bottom. The grid point resolution in this plane is 512 x 65, though only 51 x 33 vectors are shown.

IMPACT/APPLICATION

Small-scale boundary layer processes at the sea bed in shallow water are strongly influenced by wave motions and are key to understanding issues such as beach erosion and protection, bottom morphology, water clarity, mine burial, surface wave energy budgets, and bottom friction experienced by mean currents. Our work is an effective means of developing and testing parameterizations for small-scale processes that must be considered in larger scale modeling efforts.

TRANSITIONS

Our work has taken a new direction at the request of Tim Stanton (Naval Postgraduate School) who is making field measurements of the bottom boundary layer as a part of the Shoaling Surface Wave Experiment (Showex). We are now emphasizing flow behavior over rough topography characteristic of the rippled bed environment found in the field. To this end we have developed and implemented a new model and are exploring flow behavior over sand ripples for realistic wave field conditions.

RELATED PROJECTS

1-Tim Stanton and Ed Thornton at the Naval Postgraduate School are making field measurements as a part of the ONR DRI on Shoaling Surface Waves. Our work is being used to interpret the field data. Stanton is using our model output to evaluate his algorithms for estimating dissipation rates in the bottom boundary layer from the raw data collected with his BCVD .

2- Kraig Winters at the University of Washington has been instrumental in developing the model for flow over complex topography. Further collaborations in model enhancements are ongoing.

3-D.N. Slinn, National Science Foundation, Physical Oceanography, Along-Slope Current Generation by Obliquely Incident Internal Waves. 1999-2002. The same boundary layer computer models are used in LES mode, with density stratification turned on, to examine feedback between wave motions and mean currents in larger scale benthic boundary layers. Model enhancements developed in either project, such as improved numerical techniques or new physical capabilities such as the terrain following coordinate system, are adopted in both projects.

4-D.N. Slinn, Office of Naval Research, 321CD, Coastal Dynamics, Nonlinear Time Dependent Currents in the Surfzone. 1999-2002. Coupling of wave field and mean current interactions is the focus of this intermediate scale nearshore modeling study. Relatively simple parameterizations for bottom boundary layer dissipation are used in the nearshore circulation model that can be improved by insight gained from the present study of wave and current energy dissipation rates and bottom friction. Numerical experiments have shown that nearshore circulation predictions are sensitively dependent on bottom friction parameterization.

REFERENCES

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Trowbridge, J., Madsen, O. S., 1984: Turbulent wave boundary layers 1. Model formulation and first-order solution, J. Geophys. Res., 89, 7989-7997.